

Power-law temporal auto-correlations in day-long records of human physical activity and their alteration with disease

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We investigate long-duration time series of human physical activity under three different conditions: healthy individuals in (i) a constant routine protocol and (ii) in regular daily routine, and (iii) individuals diagnosed with multiple chemical sensitivities. We find that in all cases human physical activity displays power law decaying temporal auto-correlations. Moreover, we find that under regular daily routine, time correlations of physical activity are significantly different during diurnal and nocturnal periods but that no difference exists under constant routine conditions. Finally, we find significantly different auto-correlations for diurnal records of patients with multiple chemical sensitivities.

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Healthy free-running physiologic systems have complex self-regulating mechanisms which process inputs with a broad range of characteristics [1], and may generate signals that have scale-invariant dynamics [2, 3]. Physical activity is a physiologic signal of great interest due to its (i) impact on other rhythms such as heart rate, and (ii) significance for certain psychiatric or psychosomatic conditions [4, 5]. Indeed, a number of researchers has used actigraph recordings to classify types of motion—such as sitting, moving or standing [6]—with the goal of developing ambulatory methods for the diagnosing of attention-deficit hyperactivity disorder in children [7]. In such applications, the advantage of using actigraph recordings is that it may replace more limiting, cumbersome, and intrusive techniques such as videotaping [8]. Surprisingly, up to now there has been no attempt to quantify the time correlations of the fluctuations in the levels of physical activity in “free-running” ambulatory settings or their alteration under special conditions, such as constrained activity or psychiatric disease [9].

In this Letter, we study long-duration time series of human physical activity under two different conditions: a constant routine (CR) protocol where physical activity and postural changes are kept to a minimum [10], and (ii) regular daily routine (RDR). We find that physical activity displays power law decaying temporal correlations for these conditions. Moreover, we find that during diurnal periods the time correlations of physical activity are significantly different for regular daily routine and CR

protocols. In contrast, we find no differences between diurnal and nocturnal periods for the CR protocol while we find significant differences between diurnal and nocturnal periods for the regular daily routine. Further, we find similarities between the CR patterns of human physical activity and those of nocturnal periods for regular daily routine [11].

Our finding of long-range time-correlations in activity of healthy individuals under regular daily activity and the change in those correlation properties under controlled conditions, suggests that possibility that the fractal index characterizing the long-range auto-correlations of the time series of physical activity may be an additional probe [4] of the abnormal patterns of physical activity of patients with psychiatric disorders such as depression, bipolar disorder, or schizophrenia [12], and with psychosomatic illnesses associated with exaggerated fatigue. We test this possibility with data collected for individuals diagnosed with multiple chemical sensitivities (MCS). This is a disease [13] characterized by a positive chemical exposure history and multi-system symptoms, such as fatigue, headache, sleep disturbance, and myalgia, which are elicited after exposure to various chemical compounds [14]. The clinical picture of MCS is shown [14] to largely overlap with that of other psychosomatic illnesses with severe fatigue symptoms [15, 16]. Interestingly, we find a *significant difference* in the degree of diurnal auto-correlations in physical activity for MCS patients and healthy controls leading a regular daily routine.

We analyze datasets from seven healthy, non-smoking male subjects [17] (ages: 21–30 yr). For six of the subjects, we obtained two datasets per subject, the first under CR conditions, and the second under regular daily

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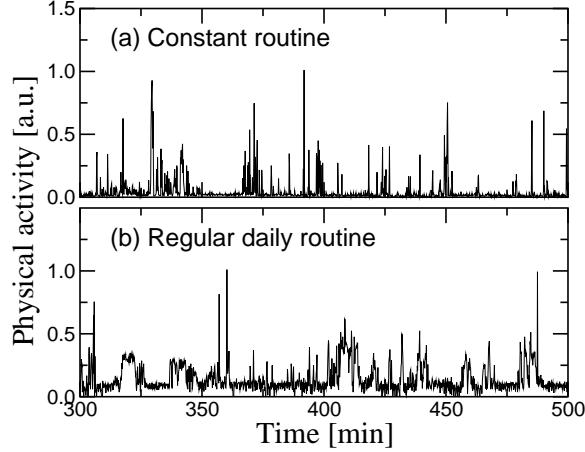


FIG. 1: Magnitude of physical activity in arbitrary units (a.u.) for (a) subject #2 during CR conditions, and (b) the same subject during regular daily routine. Note how the episodes of “sustained” physical activity are reduced during CR conditions.

routine conditions [10, 18, 19]. We recorded [18] body acceleration using a portable, *waist-worn*, long-term ambulatory monitoring device (Amx720, Nihon-Koden Wellness Corporation, Japan). The monitoring device has two shock sensors that measure body acceleration at the waist in the vertical and horizontal directions with a sensitivity of $0.08g$. The acceleration was recorded after being full-wave rectified and integrated over 8 s intervals [18]. In the present study, we consider only body acceleration in the vertical direction.

Figure 1 displays vertical acceleration at the waist for subject #2 for both CR protocol and regular daily routine. Vertical acceleration at the waist is a good proxy for physical activity because it correlates to *entire body motion*. The figure suggests a decrease in the number of episodes of sustained physical activity during CR but the quantitative nature of such time organization is not clear from the graph. Thus, we apply the detrended fluctuations analysis (DFA) method to quantify long-range time-correlations in the physical activity time series [3, 20]. The DFA method is defined as follows: One first integrates the physical activity time series. One then divides the time series into “boxes” of length n and perform, in each box, a least-squares polynomial fit of order k fit to the integrated signal. Next, one calculates in each box the root-mean-square deviations of the integrated signal from the linear fit. The basic idea is that the polynomial fit represents the local trend in each box while the magnitude of the fluctuations around the trend signals the degree of the time correlations in the signal.

This procedure is repeated for different box sizes (time scales) n . For fractal signals one finds a power-law relation between the average magnitude of the fluctuations $F(n)$ and the number of points n

$$F(n) \sim n^\alpha, \quad (1)$$

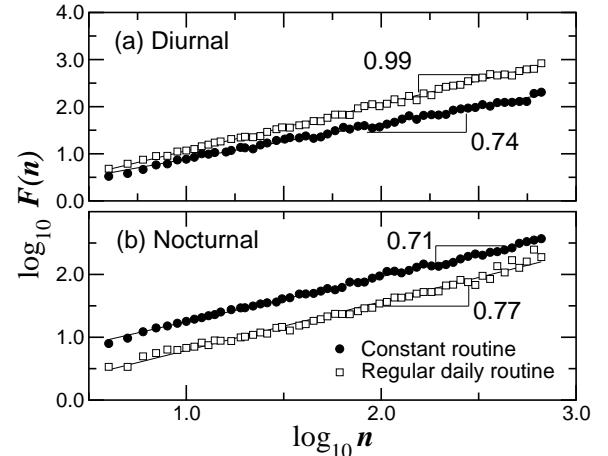


FIG. 2: Long-range time correlations in human voluntary physical activity. Double-logarithmic plot of the DFA function $F(n)$ versus time scale n for subject #2 under the CR protocol and under regular daily routine for (a) diurnal and (b) nocturnal periods. We segmented each record into blocks of 2,500 points and performed the DFA analysis on each block. We choose this block length because it provides good time resolution while keeping errors in the estimation of the scaling exponents small. For all cases, we find close agreement with a linear dependence, suggesting a power law increase of $F(n)$. We tested this assertion by considering different time-scale ranges for the power law fit. We found that the exponent estimates were nearly independent of the fitting range and selected the fitting range $16 \leq n \leq 200$. For the nocturnal period there appears to be no significant difference between the exponent values for CR or regular daily routine. In contrast, there is a marked difference between the exponent values for the diurnal period.

where the scaling exponent α quantifies the degree of the correlations. Uncorrelated time series yield $\alpha = 0.5$, long-range anti-correlations result in $\alpha < 0.5$, and long-range positive correlations results in $\alpha > 0.5$.

In Fig. 2, we show the results of the DFA analysis for subject #2 in our database. We consider separately diurnal and nocturnal periods because of recent reports indicating altered physiologic control during sleep [21, 22]. It is visually apparent that the data for diurnal and nocturnal periods and for both the CR protocol and the regular daily routine follow straight lines in the double-logarithmic plots. This fact confirms our expectation that Eq. (1) holds. Surprisingly, we find different exponents during diurnal periods for CR and regular daily routine while we find similar exponent values for the nocturnal periods. This finding suggest a difference in the type of voluntary physical activity [23] during diurnal regular daily routine.

We test this finding for all other subjects in the database (Fig. 3 and Table I). Our analysis reveal a value of α systematically larger for regular daily routine than for CR during the daytime. We test this possibility with two statistical test [24]: the Student t-test, which tests differences in mean values under the assumption of Gaussianity of the random variables, and the Kolmogorov-

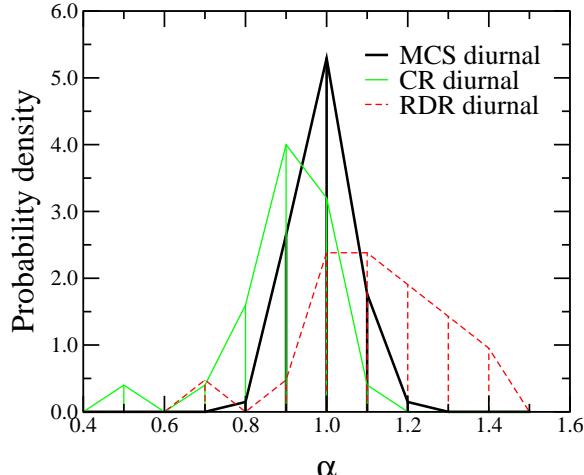


FIG. 3: Probability density function of the DFA exponent α of diurnal records for the three conditions considered in our study. We find that the three distributions are statistically different according to the KS test at the 99.99% confidence level.

Smirnov (KS) test, which is a non-parametric test for distributions. We find that the difference in the average values of α for the regular daily routine and CR during diurnal periods is significant at the $p < 0.001$ level for both Student's t-test and the KS test. We also find that the difference in the average values of α for the regular daily routine and CR during nocturnal periods is not significant [25].

To investigate the medical significance of our results for the characterization of psychiatric and psychosomatic diseases, we next analyze data collected over a seven day period for four individuals (ages: 34–47 yr) diagnosed with MCS [26]. We find that the auto-correlations of the diurnal physical activity time series are characterized by a DFA exponent $\alpha = 0.93 \pm 0.001$ (Table 1 and Fig. 3) which we find to be significantly different from the results for healthy subjects at the $p < 10^{-5}$ level for both the Student's t-test and the KS test.

A key finding of this study is that voluntary physical activity has a power-law decaying time correlations whose characteristic index α changes when patterns of physical activity are controlled or disturbed. For diurnal periods, we measure a smaller value of α for CR than for regular daily activity. The picture emerging from our results raises the possibility that conditions such as hyperactivity, depression and other psychiatric and psychosomatic disorders will modify the “pull” of daily routines on physical activity and lead to different values of α . Hence, it is plausible that our finding of fractal correlations in the activity levels of healthy mature individuals provides a new window into the study of psychiatric and maturation disorders which is not hindered by complex (and more falsifiable) procedures such as classifying motion types. Indeed, we test this possibility for MCS patients and confirm that correlations in activity are altered by disease. Further, we have also found [27] changes in cor-

TABLE I: Exponent values for the two protocols and two time periods considered in our analysis. In the table, CR stands for constant routine, RDR stands for regular daily routine, and MCS for multiple chemical sensitivities, S indicates the number of subjects for which we have measurements in each group and N the number of different exponent estimates, α and σ_α are the average and standard deviation, respectively, of the DFA exponents for each group.

| Group | S | N | α | σ_α |
|---------------|-----|-----|------------------|-----------------|
| CR diurnal | 7 | 25 | 0.85 ± 0.01 | 0.03 |
| RDR diurnal | 6 | 21 | 1.08 ± 0.01 | 0.04 |
| MCS diurnal | 4 | 68 | 0.93 ± 0.001 | 0.008 |
| CR nocturnal | 7 | 14 | 0.89 ± 0.02 | 0.08 |
| RDR nocturnal | 6 | 12 | 0.95 ± 0.04 | 0.12 |

relation for patients with a severe fatigue illness called chronic fatigue syndrome [15, 16].

Our findings are also of importance because of their implications on the question of the influence of fractal stimuli, such as physical activity, on the properties of other rhythms such as heart rate. Specifically, it has been recently shown that time series of healthy human interbeat intervals belong to a special class of complex signals that display multifractal properties [28, 29]. An explanation is that the neuroautonomic control mechanisms—in the presence of even weak external noise—*endogenously* generate multifractal dynamics.

A recent study showed that the heart rate variability of healthy adults displays similar multifractal properties for CR and regular daily routine conditions [19]. In contrast, sympathetic or parasympathetic blockades were found to lead to a significant loss of complexity of HRV [19]. It would thus appear that—in contrast to neuroautonomic control—voluntary physical activity may not be an important factor in the generation of the fractal [30] or multifractal properties of heartbeat dynamics [19]. However, an important assumption for validating the above conclusion is that voluntary physical activity during the CR protocol [10] *is significantly different from that during regular daily routine*. Indeed, if during CR conditions there is only a decrease of the amplitude in the physical activity, then one would need to show that such a decrease during the CR protocol lowers the amplitude of the physical activity below a threshold value in order to justify the endogenous character of the multifractal properties of heartbeat dynamics. Our finding that the fractal time organization of physical activity during CR conditions is significantly different from the time organization during diurnal regular daily routine strengthens the conclusion that voluntary physical activity is not responsible for the multifractal character of heartbeat dynamics.

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[11] This finding confirms the basic assumption behind the use of the CR protocol—i.e., that the CR protocol al-

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[25] In this Letter, we do not analyze in detail the absolute activity level. The reason is that the use of absolute activity counts recorded by actigraphs for analysis of human activity has raised a number of serious concern in the scientific literature (see Ref. [18] for details). In contrast, the *relative* changes measured by the accelerometer, which is the quantity we are concerned with in this Letter, are not hindered by such methodological concerns [18].

[26] Each patient gave informed consent to participate in this study after the test protocol was fully described. This study was reviewed and approved by the ethics committee of The University of Tokyo Hospital. The method of data collection was the same as that for healthy subjects.

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